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SOFT X-RAY SPECTROSCOPY WITH EXOSAT

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Summary

With the 500 and 1000 l/mm transmission gratings aboard the *European X-ray Observatory SAT*ellite (*EXOSAT*) we have measured medium-resolution ($\Delta\lambda \cong$ 5 A at 100 A) spectra of some ten objects of various categories such as isolated white dwarfs, cool stars with convective mantles, cataclysmic variables (e.g. AM Her) and a high-luminosity X-ray source (Sco X-1).

The instrument configuration was mostly such that one low-energy telescope was used as a photometer, while the other telescope was used as a spectrometer with the 500 l/mm grating inserted.

The white dwarf spectra were measured between about 60 and 300 A. They show a continuum with no clear evidence of aborption and emission lines except for the He II absorption edge at 227 A in the spectrum of Feige 24. For the cooler (28 000 K) white dwarf Sirius B the emission is peaked between about 100 and 160 A and limited to about 200 A, which can be expected from atmospheric model spectra of DA white dwarfs. The soft X-ray emission of the hotter ($\geq$ 60 000 K) DA white dwarfs (HZ43, Feige 24) is also interpreted in terms of photospheric emission. In the HZ43 spectrum the absorption edge is apparently absent which sets a stringent upper limit to the abundance ratio He/H of about 10^{-5}. On the other hand the spectrum of Feige 24 shows a dominant absorption edge, implying He/H $\geq 10^{-3}$. Moreover, here the shape of the continuum may be indicative of a stratification of element abundances in the outer atmosphere.

The active late-type stars σ^2 CrB and Capella show in the spectral region between 90 and 140 A lines from Fe XVIII to Fe XXIII, indicative of the presence of hot ($\cong$ 10 MK) plasma like that in a Solar flare. On the contrary, the spectrum of the cooler corona of the star Procyon does not show the hot Fe XXII and Fe XXIII lines but instead a blend at 175 A of Fe IX, X and XI lines that are formed in a typically quiet corona of a temperature around 1.5 MK. Also the ratio of Fe XVI (65 A) and Si XII (48 A) lines is a good indicator of temperature in the spectra. From the spectral intensities and the additional results of the simultaneous multi-color photometry coronal temperatures and emission measures are derived. There are indications in the spectra that the emission should be interpreted in terms of differential emission measure distribution models.

1. Introduction

The first free-standing gold bar transmission gratings we made by holographic techniques (Dijkstra and Lantwaard 1975, Dijkstra 1976, Schnopper et al. 1977) were implemented in the objective grating spectrometer aboard the astronomical *EINSTEIN* X-ray observatory (see Seward et al. 1982). The gratings in the *European X-ray Observatory SAT*ellite (*EXOSAT*) were made by an improved lithographic technique of contact printing producing replica gratings from a master mask (Dijkstra et al. 1978). The grating line densities are 500 and 1000 lines per mm.

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The use of transmission gratings allows the study of point-like cosmic soft X-ray sources like isolated white dwarfs, stellar coronae and cataclysmic variables with comparatively high efficiency combined with a moderate resolution ($\Delta\lambda$ typically $\cong$ 3 to 6 A from λ = 10 to 200 A for the 500 l/mm grating) in a large dynamic range that is measured simultaneously.

2. Schematical design of EXOSAT spectrometer

Fig. 1 gives a schematic layout of the optical arrangement showing convergent bundle from Wolter I telescope, transmission grating ring and one first-order focus at a given wavelength (**a**) and an enlarged view of two-loop focal curve for one grating ring (**b**), where p is the displacement from the first-order image (z_0) and a the total extent of the focal pattern determined by grating aberrations. Ray-tracing computer calculations for the double nested *EXOSAT* telescope (Dijkstra et al. 1978) give a more complicated pattern consisting of a superposition of four loops. The grazing incidence Wolter-type mirror has a net total geometric area of about 90 cm². The grating consists of 24 elements mounted on a ring 3 cm behind the mirror. The spectrum is imaged 85 cm behind the grating in the focal plane on a channel multiplier array (CMA) detector. For a point source on axis the zero-order image is in the center of the field of view, the plus and minus first and higher orders are formed perpendicularly to the grating lines symmetrically around the 0th order. There are two identical telescopes on board *EXOSAT*, one with the 500 l/mm grating and one with the 1000 l/mm grating. The wavelength coverage with the 500 l/mm grating is for an on-axis source $\pm$ 450 A and the first-order linear dispersion 42.5 μm/A. The resolution of the 500 l/mm grating is $\Delta\lambda \cong 3$ A for $\lambda < 70$ A (determined by effects of mirror and finite resolution of image detector) and $\Delta\lambda \cong 0.04\lambda$ at longer wavelengths (dominated by grating aberrations, e.g. coma). Corresponding values for 1000 l/mm grating differ by a factor of about two.

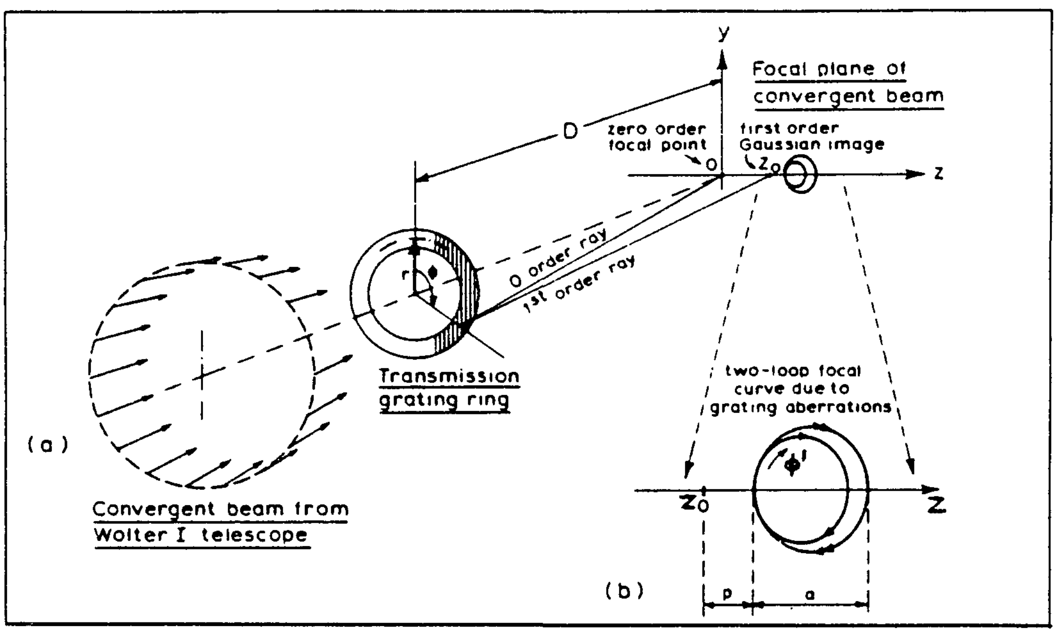

Fig. 1. Schematic layout of optical arrangement of *EXOSAT* objective grating spectrometer (see text).

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The effective area of the spectrometer with the 500 l/mm grating is shown in Fig. 2 for various filter combinations (lex thin: thin (3000 A) lexan; lex thick: thick (4000 A) lexan; Al/P: Aluminum/Parylene; Ppl: Polypropylene; Boron: Boron). The efficiency of the 1000 l/mm grating spectrometer is comparable to this.

For a more detailed instrumental description see Brinkman et al. (1980).

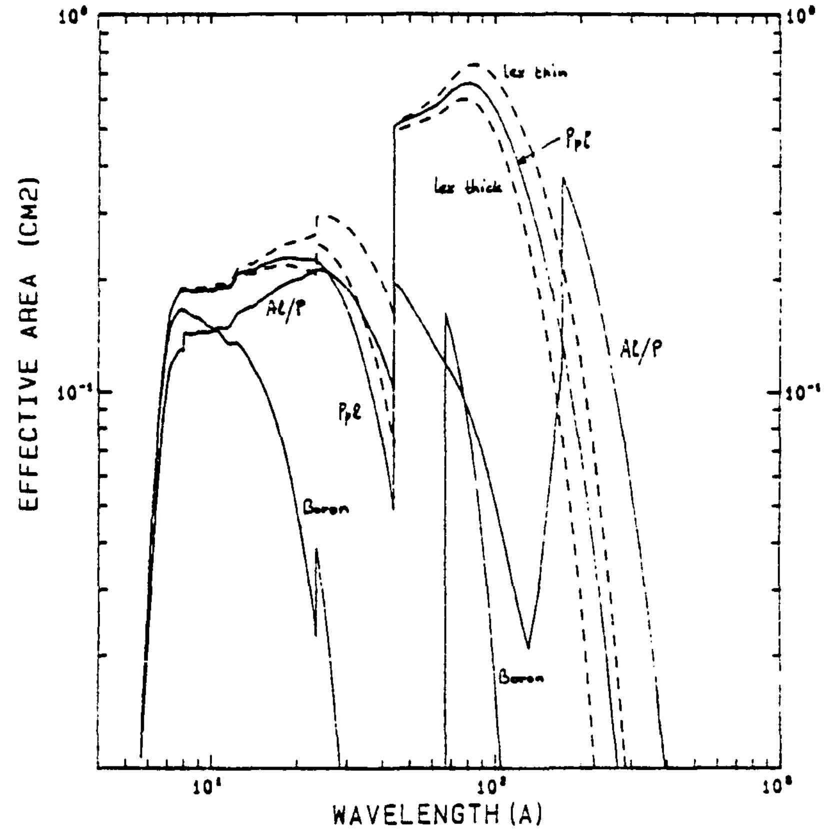

Fig. 2. Efficiency of 500 l/mm grating spectrometer (see text).

3. Observational results

3.1. Isolated white dwarfs

Observations with the *EINSTEIN* observatory have yielded a few new detections (Kahn et al. 1984) above the previously known sources such as Sirius B, HZ 43 and Feige 24.

Predictions on the basis of photospheric models (e.g. Wesemael et al. 1980) indicate that the bulk of the X-ray emission from hot (T_{eff} > 30000 K) white dwarfs falls in the XUV region. Therefore, the extension of the sensitivity towards longer wavelengths of *EXOSAT* compared to *EINSTEIN* makes it a suitable tool for studying the spectra of these objects. Indeed, recent *EXOSAT* results (Heise et al. 1984a) have demonstrated that isolated white dwarfs constitute a class of extreme soft X-ray emitters. Out of 12 pointings at least 8 are detected to be quite bright. They are mostly of spectral type DA or the hotter DB.

Spectra obtained with the *EXOSAT* grating spectrometer of the white dwarfs Feige 24, HZ 43 and Sirius B are shown in Fig. 3 and will be shortly discussed here. For further details I refer to a forthcoming paper by Heise et al. (1984b).

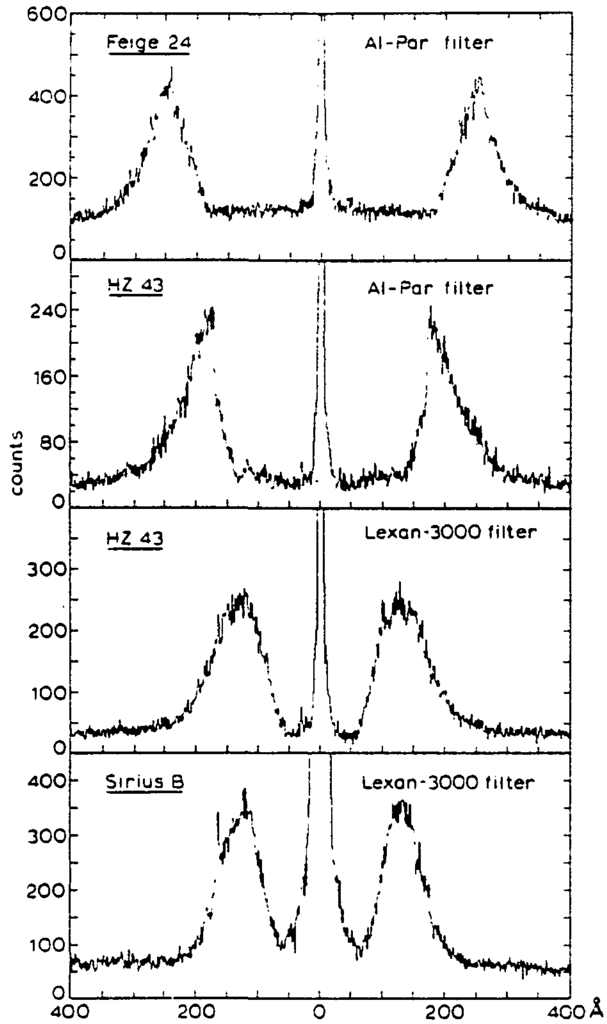

Fig. 3. *EXOSAT* 500 l/mm grating spectra of white dwarfs.

The spectrum of the comparatively cooler (≅28000 K) white dwarf Sirius B is peaked between 100 and 200 A, as is indeed predicted by the atmospheric model spectra of DA white dwarfs calculated by Wesemael et al. (1980). For the hotter dwarfs (> 40000 K) the models indicate an extension of the emission spectrum towards wavelengths above 200 A, which is indeed seen in the spectra of the hotter (T_{eff} near 60000 K) DA white dwarfs Feige 24 and HZ 43. In this case the *EXOSAT* observations provide the possibility of detecting the He II absorption feature. From the disappearance of helium lines in the optical spectra we know that the He/H abundance ratio should be lower than about 1% (e.g. Buess 1970), but model calculations predict already noticeable jumps at the He II Lyman absorption edge at 227 A for He/H abundance ratios above about 10^{-5}.

The spectrum of HZ 43 is everywhere well fitted by a pure hydrogen model spectrum. No jump at 227 A is observed, which implies a stringent upper limit of He/H $< 10^{-5}$. This contradicts the results obtained by Malina et al. (1982) which claim to find in a spectrum with a rocket-borne EUV imaging spectrometer a jump at the He II edge of a factor of 2, consistent with He/H abundance ratios in the range 1.5–6 10^{-5} for T_{eff}=45000–60000K. It should be remarked that most of their data points together with the measurements from Apollo-Soyuz and Voyager presented in their Fig. 2 can be reasonably fitted by a pure hydrogen model with T_{eff}=60000K and a hydrogen column density N_H=5 10^{17} cm^{-2}.

The spectrum of Feige 24 steeply declines below 230 A. It is neither fitted by a pure H model nor a pure He model. Reasonable fits require an abundance ratio He/H of at least about 10^{-3}, but still there are significant discrepancies on both sides of the peak. It will be investigated whether models with a stratification of element abundances give better agreement.

3.2. Stellar coronae

Grating spectroscopy has its most obvious application in the measurements of hot optically thin sources which are expected to display in their X-ray spectra many interesting emission line features from highly ionized elements.

The *EINSTEIN* observations have provided us with a picture of stellar coronae based on a lot of detections of X-rays from nearly every type of star (e.g. Vaiana et al. 1981, Mewe 1984), but at the same time they pose many questions concerning the structure of the sources and the nature of the X-ray generating mechanisms. It is interesting that the surface fluxes of late-type stars cover a range extending from 10^3 to 10^8 erg cm^{-2} s^{-1}, that is from more than ten times weaker than a Solar coronal hole up to ten times brighter than Solar active regions (Schrijver 1983)! Medium- to high-resolution spectroscopy is required to obtain accurate estimates of gas temperatures, emission measures and densities.

The few observations with the *EXOSAT* spectrometer are limited to some of the brighter stars for reasons of obtaining good statistics. We have chosen three late-type stars with widely different levels of intrinsic X-ray activity: Procyon (α CMi <u>F5IV</u>+DF), Capella (α Aur G6III+<u>F9III</u>) and σ^2 CrB (<u>F6V</u> + G1V) (underlined are the candidate X-ray emitters). The photometric *EXOSAT* observations (Brinkman et al. 1984) simultaneously with the grating measurements and earlier *EINSTEIN* observations (Schrijver et al. 1984) yield that these stars have increasing X-ray surface fluxes of about 2, 10 and 10^3 times that of the average Sun, respectively, consistent with the increasing rotation rates of these stars. Fig. 4 shows a composition of the spectra of these objects juxtaposed to each other on the same wavelength scale. The net observing times were 20 hrs for the two RS CVn stars and 6.5 hrs for Procyon. Various interesting line groups are indicated by letters a to g. Their temperature behaviour shown in Fig. 5 was calculated by folding theoretical spectra (Mewe et al. 1982, 1984) for an optically thin plasma with the instrumental response function.

A quick analysis (see also Brinkman et al. 1984) of these line blends shows for example that the "Solar flare" lines from $2s$–$2p$ transitions in Fe XXII (e) and Fe XXIII (f) are prominent for the RS CVn stars, but are absent in the Procyon spectrum, whereas in the latter spectrum a line blend around 175 A is present, which does not occur in the spectra of Capella and σ^2 CrB. These lines can be probably attributed to lines from Fe IX, X and XI ions which are formed in a cool quiet corona of about 1.5 MK, but which are comparatively faint in a hot corona of about 10 MK like those around the RS CVn stars. Furthermore, it is seen that the intensity ratio Fe XVI (c) / Si XII (b) decreases going from Procyon to σ^2 CrB. The photometric measurements indicate coronal temperatures of about 2, 5–10 and 6–12 MK for α CMi, α Aur and σ^2 CrB, respectively. Indeed from the temperature behaviour of the considered lines (compare Figs. 4 and 5) one can infer that the spectra from bottom to top indicate an increasing coronal temperature. The simultaneous appearance of lines from many different ionization stages in the spectra of the two hotter stars suggests that a differential emission measure distribution probably better fits the spectra than a single-temperature model does. However, further detailed analysis is still in progress to derive accurate physical parameters for the X-ray emitting structures.

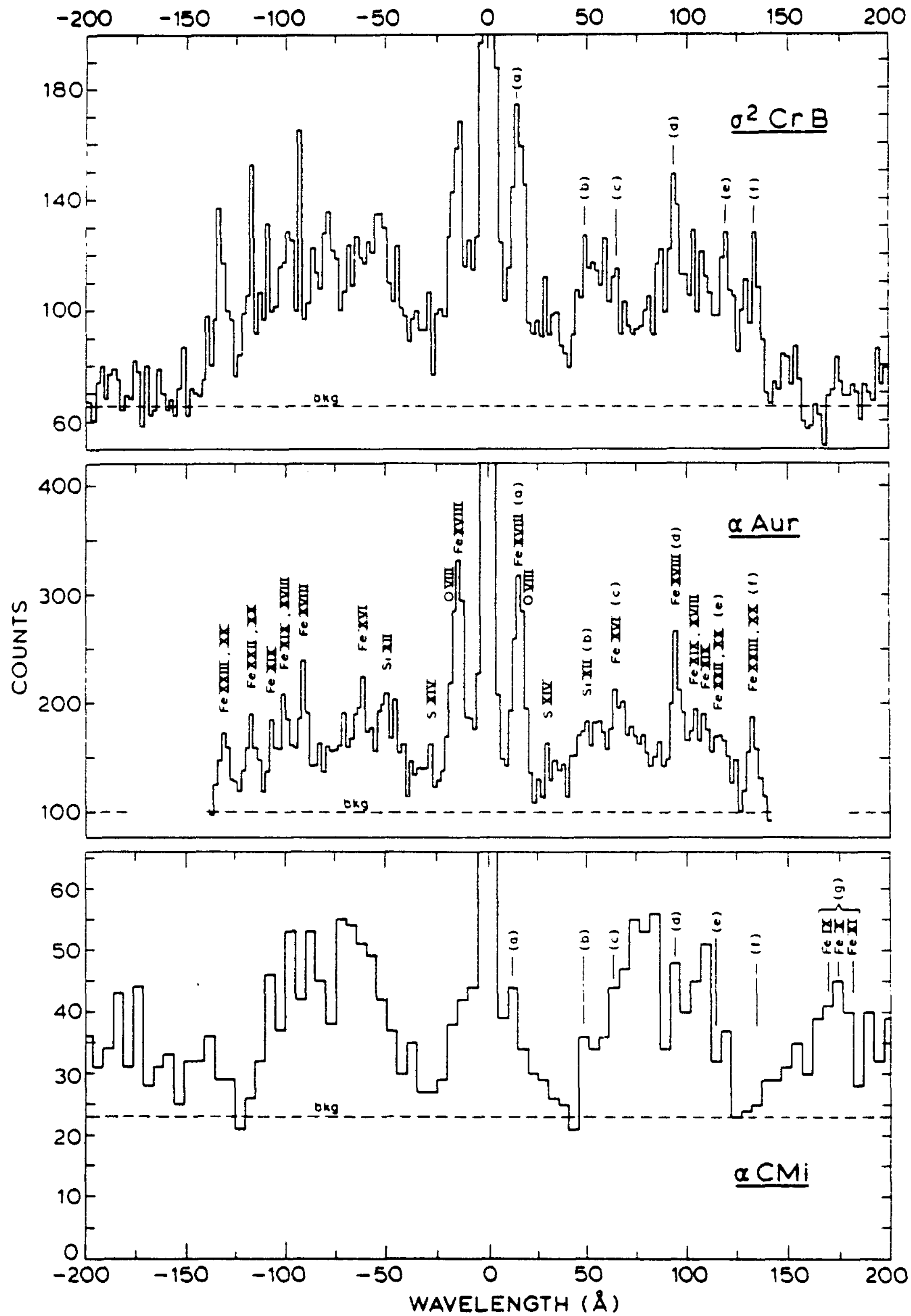

Fig. 4. *EXOSAT* 500 l/mm grating spectra of late-type stars. Letters a to g indicate line groups with different temperature behaviour (see Fig. 5). In all three cases the thin lexan filter was used.

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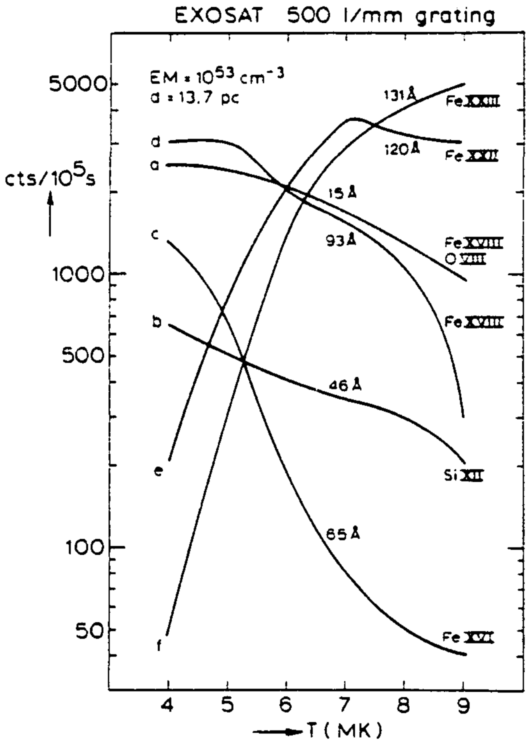

Fig. 5. Temperature behaviour of intensities of various line blends indicated in the spectra given in Fig. 4. The assumed widths of the blends correspond to about the spectral resolution. For each blend only the strongest line is indicated.

3.3. Miscellaneous sources

A few other sources such as the low-mass binary Sco X-1 and the magnetic white dwarf (polar) AM Her have been measured. The spectra of Sco X-1 (in both 500 and 1000 l/mm grating) contain features that are indicative of absorption edges and of line emission. During the observations these features varied strongly in time. The spectrum (detected with 500 l/mm grating) of AM Her comes from the optically thick soft X-ray component and can be fitted by blackbody radiation of temperature about 3 10^5 K and interstellar absorption with a column density N_H=8 10^{19} cm^{-2}. It is interesting that during the observations in summer 1983 the soft X-ray radiation was in anti-phase with the optically thin hard X-rays and this result will allow a critical discussion of the various models that exist for the generation of the soft X-ray component and the geometry of the emission region (see Heise et al. 1984c). Data analysis of these sources is still in progress.

4. Conclusions

These early results have demonstrated the potential of medium-resolution soft X-ray spectroscopy with transmission gratings in the study of astrophysical sources. We have seen that in the study of extreme soft sources like white dwarfs the main thrust of the *EXOSAT* spectrometer comes from the extension of the wavelength range. The extension towards longer wavelengths is also very important in studying the hot coronal sources which exhibit in their spectra groups of strong iron lines indicative either of hot (10 MK) plasma components (Fe XXII and XXIII lines around 130 A) or the cooler (1.5 MK) quiet corona (Fe IX-XI at 175 A). The analysis of these medium-resolution spectra already shows a glimpse of the enormous possibilities of next-generation spectrometers with one or two orders improvement in spectral resolution and throughput like in *AXAF*.

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